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Dr. J. Reece Roth, Principal Investigator

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The University of Tennessee
404 Andy Holt Tower
Knoxville, TN 37996-0140

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9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AF Office of Scientific Research
801 N Randolph St. Room 732
Arlington, VA 22203

Dr. John Schmisseur
(703) 696-6962
john.schmisseur@AFOSR.AF.mil

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14. ABSTRACT We took wind tunnel data and were able to demonstrate low speed (below 5 m/sec) flow attachment on a NACA 0015 airfoil using OAUGDP plasma actuators. We were able further to demonstrate that only one actuator was sufficient to produce re-attachment, and that this actuator should be located not at the site of the flow separation bubble, but at the leading edge of the airfoil. The plasma actuators not only re-attached the flow, but also stabilized the downstream flow, reduced vortex formation, and increased the stall angle of the airfoil. During these wind tunnel tests, we also demonstrated peristaltic flow acceleration by polyphase RF signals driving a phased sequence of OAUGDP plasma actuators, and we demonstrated the reversal of the peristalticaly-induced flow with the reversal of the phase of the driving RF voltage.

We also developed and investigated mechanically and electrically robust paraelectric, peristaltic, and combined paraelectric and peristaltic ceramic plasma actuator panels. Among these was a three-dimensional electrohydrodynamic flow acceleration duct that functions like a Glauert wall jet. The most promising design was the combined paraelectric and peristaltic panel, and the EHD flow acceleration duct, in which peristaltic flow from phased electrodes is given an additional boost by paraelectric momentum addition, with no momentum addition counter to the dominant flow to induce turbulence in the boundary layer. At the end of the contract, the EHD duct produced exit velocities more than 9 meters/second using paraelectric effects alone. We also achieved up to 7 meters/sec by pure peristaltic acceleration. We also found that one or more plasma actuators in series could be modeled as a classical Glauert wall jet in the region outside the plasma where electrohydrodynamic effects are no longer dominant.

15. SUBJECT TERMS
plasma actuators, OAUGDP, electrohydrodynamics, EHD, EHD flow control, flow re-attachment, munitions steering, paraelectric flow acceleration, peristaltic flow acceleration

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FINAL REPORT Grant AF F49620-01-1-0425 (ROTH) – "An Investigation of Flow Acceleration and Electromagnetic Absorption Phenomena Induced by Paraelectric and Peristaltic Electrohydrodynamic Effects of the One Atmosphere Uniform Glow Discharge Plasma"

FINAL REPORT June 1, 2001 to November 30, 2003

Principal Investigator: J. Reece Roth, Ph.D.
University of Tennessee Plasma Sciences Laboratory (http://plasma.ece.utk.edu)
Department of Electrical and Computer Engineering
Knoxville, TN 37996-2100
Voice, (865) 974-4446; Fax, (865) 974-5483; E-mail, jrr@utk.edu

CONTENTS

This document is the final report on research activities supported by Air Force grant AF F49620-01-1-0425 (Roth), entitled "An Investigation of Flow Acceleration and Electromagnetic Absorption Phenomena Induced by Paraelectric and Peristaltic Electrohydrodynamic Effects of the One Atmosphere Uniform Glow Discharge Plasma" that was managed by Dr. John Schmisseur of the AFOSR. It covers the 30-month period from June 1, 2001, the inception of the grant, to its end on November 30, 2003. This grant supported exploratory research in a new technical area, the use of electrohydrodynamic (EHD) effects for aerodynamic acceleration and flow control by plasma actuators, using the One Atmosphere Uniform Glow Discharge Plasma (OAUGDP™) developed at the University of Tennessee's Plasma Sciences Laboratory. The topics investigated in this research program are listed in Section II of the Table of Contents below. Of these, the first 5 were contemplated in the original proposal on the basis of which this work was originally funded; and the remainder are "targets of opportunity" that emerged from the exploratory nature of the research. Topic 7 on the high velocity (ten meters/second) EHD duct involves proprietary material contained in the second annual report to AFOSR that is not repeated here, to maintain the public nature of this document.

EXECUTIVE SUMMARY

During this grant, we took data during three experimental campaigns at the 7 x11 Low Speed Wind Tunnel at the NASA Langley Research Center. During those experimental runs, we were able to demonstrate low speed (below 5 m/sec) flow attachment on a NACA 0015 airfoil using OAUGDP plasma actuators. We were able further to demonstrate that only one actuator was sufficient to produce re-attachment, and that this actuator should be located not at the site of the flow separation bubble, but at the leading edge of the airfoil. The plasma actuators not only re-attached the flow, but also stabilized the downstream flow, reduced vortex formation, and increased the stall angle of the airfoil. During these wind tunnel tests, we also demonstrated peristaltic flow acceleration by polyphase RF signals driving a phased sequence of OAUGDP plasma actuators, and we demonstrated the reversal of the peristalticaly-induced flow with the reversal of the phase of the driving RF voltage.

We developed our microwave plasma diagnostic system for OAUGDP (and other) plasmas to the point where we were able to make time-averaged measurements of the electron number density and estimates of the electron collision frequency of air OAUGD plasmas. In addition, we were able to make 60 Hz time resolved measurements of the electron number density and collision frequency in fluorescent light tube plasmas, and were able to resolve the differences between the standard and "green" (i.e. reduced mercury) commercial tubes. This work was so promising in its own right that a group has been formed at UT and NIST to develop this diagnostic as a standard diagnostic instrument, either with support by MURI Topic 22, or other sources. As part of this work, we had our only technical disappointment: a thin layer of OAUGDP plasma does not have enough turbulence or collisionality to significantly absorb incoming microwave radiation, so it is not a candidate for stealth applications.

We also developed and investigated mechanically and electrically robust paraelectric, peristaltic, and combined paraelectric and peristaltic ceramic plasma actuator panels. Among these was a three-dimensional electrohydrodynamic flow acceleration duct that functions like a Glauert wall jet. The pure peristaltic panel was found to be of limited interest because of the turbulence generated by counter-flowing jets originating on the upstream side of the phased electrode strips. The most promising design was the combined paraelectric and peristaltic panel, and the EHD flow acceleration duct, in which peristaltic flow from phased electrodes is given an additional boost by paraelectric momentum addition, with no momentum addition counter to the dominant flow to induce turbulence in the boundary layer. At the end of the grant, the EHD duct produced exit velocities more than 9 meters/second using paraelectric effects alone. We also achieved up to 7 meters/sec by pure peristaltic acceleration. Promising work continues, and we have since reached higher velocities, using combined paraelectric and peristaltic flow acceleration.

Smoke flow studies were performed to document the presence or absence of boundary layer turbulence for the types of plasma actuator panel under development, and for various operating conditions. We found that the induced flow above the paraelectric and combined paraelectric and peristaltic panels was laminar over the range of operating conditions studied, with the flow lines parallel to, or slowly descending to the panel surface. In no case did we see the wall jet angle upward, or any other evidence of an upward component of wall jet momentum. This horizontal momentum addition of the plasma actuators likely results because the electrodes

were flush with the surface (no more than 0.06 mm high), much less than the height of the maximum of the induced jet velocity.

We took vertical boundary layer velocity profiles with a Pitot tube under a wide range of plasma actuator operating conditions. We found that the combined paraelectric and peristaltic acceleration filled in the classic wall boundary layer profile, to produce a profile that *decreased* with height, and the maximum of which occurred within the smallest vertical resolution of our Pitot system, approximately 50 microns. The velocity increase of a staged series of plasma actuators initially rises linearly with the number of actuators energized, but saturates above 10 sequential such actuators. This saturation presumably occurs because the flow "escapes" sideways from the spanwise edges of the active area of the actuator panel. We found also that the maximum wall jet velocity increases linearly with the RF driving frequency and voltage, but reaches a maximum and then declines as the frequency or voltage exceed the optimum ion trapping frequency.

We also found that one or more plasma actuators in series could be modeled as a classical Glauert wall jet in the region outside the plasma where electrohydrodynamic effects are no longer dominant. Finally, we were able to show that a panel covered with plasma actuators was robust in that a jet of pressurized air had little visible effect on the actuator plasma, a spray of water would quench the plasma only briefly, that it was possible to literally walk on an energized plasma panel, and that if the panel was impedance matched and properly connected, it was possible to touch and handle a panel while the plasma actuators were energized.

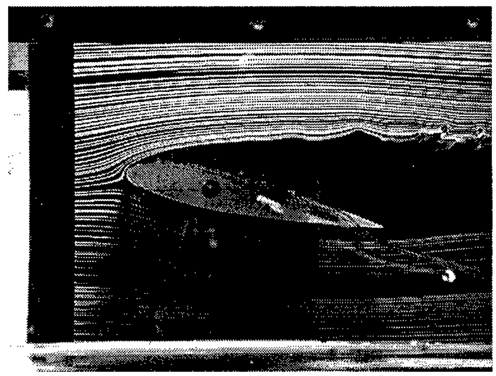
II TECHNICAL RESULTS

1.) Wind Tunnel Data on Flow Attachment using Paraelectric EHD Effects

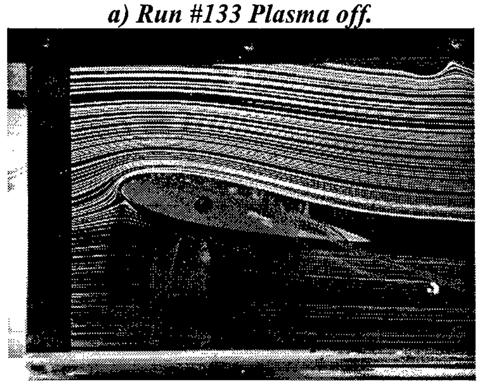
With the assistance of our collaborator, Stephen P. Wilkinson of the NASA Langley Research Center (who contributed to all wind tunnel data), a series of spanwise, parallel, asymmetric, paraelectric strip electrodes, spaced 1 cm apart, were placed on the upper surface of a NACA 0015 standard airfoil and tested in the 7 X 11 inch Low Speed Wind Tunnel at the NASA Langley Research Center. The geometry of these electrodes creates a low gas pressure in the plasma region, and each plasma actuator in the array imparts momentum to the plasma ions and to the neutral gas in the boundary layer, in the direction of the wind tunnel flow [see Section 18.6 of Roth, J. R.; *Industrial Plasma Engineering. Volume II -- Applications to Non-Thermal Plasma Processing.* Institute of Physics Publishing, Bristol and Philadelphia, ISBN 0-7503-0545-2, (2001).]. This momentum "pumps" the boundary layer flow to the rear of the airfoil, and it appeared reasonable to expect this flow to attach the free-stream flow to the airfoil at higher velocities and at higher angles of attack than would be the case without it.

The results of these wind tunnel tests were very encouraging, and indicated that significant flow attachment effects could be observed at free stream flow velocities up to two or three times the paraelectric velocity induced in the boundary layer (the latter about 3-5 meters/sec). Figure 1 illustrates smoke flow data taken at an angle of attack of 12 degrees and a free stream velocity of 2.5 meters per second. Figure 1a shows flow separation with the plasma off. Figure 1b shows the flow with all eight electrodes energized at 3.6 kV and 4.2 kHz. The flow is reattached, and there is no evidence of turbulence in the wake. It was of interest to determine how many electrodes placed at what positions on the airfoil were required to produce

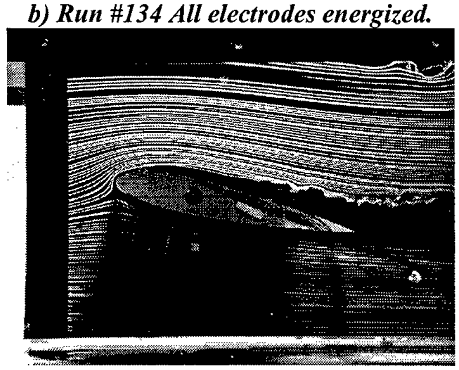
useful effects. Figure 1c shows the effect of energizing only electrode # 1 near the leading edge of the airfoil. In this case, this single electrode was nearly as effective as the eight energized electrodes in attaching the flow, but there was some indication of downstream turbulence and vortex formation. In related studies, not illustrated, it was determined that the electrodes were more effective, the closer they were to the leading edge, and that energizing more than one electrode contributed very little additional flow-attaching effect.



a) Run #133 Plasma off.



b) Run #134 All electrodes energized.



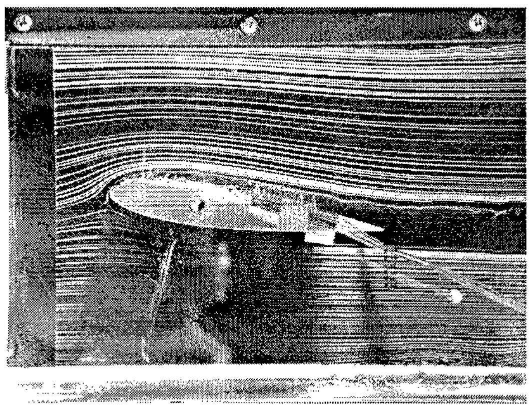
c) Run #136 Electrode #1 energized.

Figure 1 Effect of asymmetric paraelectric plasma excitation on flow attachment. Flow velocity 2.5 m/sec; angle of attack 12 degrees; 3.6 kV rms, 4.2 kHz plasma excitation.

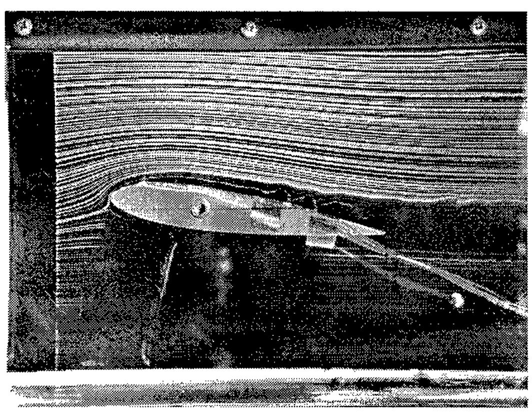
If EHD flow attachment is to replace flaps or hydraulic-mechanical actuators for flight control, they must be effective at speeds relevant to take-off and landing, up to 70 meters per second. We are just starting to explore the free stream velocities at which paraelectric flow

control will remain effective. One problem is to get the smoke flow visualization technique to work at speeds above 10 meters/sec. An example of flow attachment at higher speeds – 7.25 meters/sec – is illustrated in Figure 2. In Figure 2a is shown the attached flow with all 8 electrodes energized, and Figure 2b shows the detached flow with the plasma off. There is not a large effect at this velocity, indicating that the plasma actuator velocity (the plasma operating voltage) needs to be increased to increase the attachment effect.

The UT Plasma Sciences Laboratory has two basic patents on plasma actuators. Our work on paraelectric flow acceleration and subsonic plasma aerodynamics has attracted interest outside our laboratory. A Google search on the topic "plasma actuator" shows 47 websites or other locations now active on the subject, a topic that did not exist before our lab invented it.



a) Run 333 All electrodes energized



b) Run 325 Plasma off

Figure 2 Effect of a symmetric paraelectric plasma excitation on flow attachment. Flow velocity 7.25 m/sec; angle of attack 8 degrees; 4.0 kV rms, 4.2 kHz plasma excitation

2.) Observation of Peristaltic Flow Acceleration

Peristaltic plasma acceleration occurs when a series of parallel electrodes or plasma actuators are driven by an RF voltage sufficient to create an OAUGDP™ plasma, and each of these parallel electrodes is phased with respect to its neighbors in such a way that a horizontal electric field is generated by the traveling electrostatic wave. The physics of peristaltic plasma

acceleration is discussed in Section 18.6.3 of Roth, J. R.; *Industrial Plasma Engineering. Volume II -- Applications to Non-Thermal Plasma Processing.* Institute of Physics Publishing, Bristol and Philadelphia, ISBN 0-7503-0545-2, (2001), and is analogous to the "moving" lights on a theatre marquee.

Prior to this grant, it was not clear that peristaltic flow acceleration would work at all. Our initial demonstration of the effect used a panel with 24 electrodes energized by an 8-phase polyphase power supply, yielding 3 complete phase periods. The flow was visualized by titanium dioxide smoke, and recorded on videotape that may be accessed on the UT Plasma Sciences Laboratory Website http://plasma.ece.utk.edu, by clicking on the "videotape" button. When the panel was energized by positive phasing, the air above the surface moved in the positive direction across the panel; with negative phasing, the flow was equal in magnitude but reversed. When the phase angle between electrodes was set to zero, there was no net flow in the horizontal direction. These observations demonstrated the existence of RF-driven peristaltic EHD flow for the first time.

Our investigations of peristaltic electrohydrodynamic (EHD) flow acceleration used the 25 x 25 cm peristaltic panel shown in Figure 3, on which there are 24 strip electrodes separated by 1 centimeter. This panel was energized with an 8-phase polyphase power supply capable of supplying RF voltages *up to* 8 kilovolts at frequencies *up to* 8 kiloHertz. The panel is set up for three complete periods of 8-phase excitation, with successive strip electrodes energized at a phase angle of 45 degrees leading or lagging the previous electrode.

Our experiments showed unambiguous evidence of peristaltic flow acceleration. Exploratory tests were done in air at one atmosphere, with an RF frequency of 3.3 kHz and an

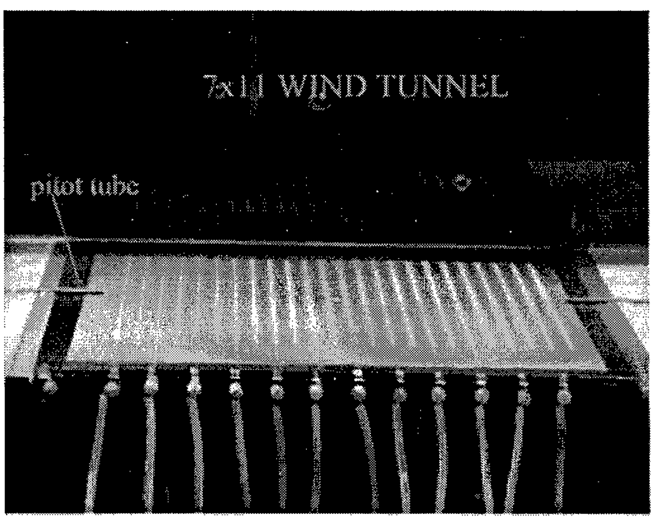


Figure 3 . Three period, 8 phase polyphase electrode panel energized for peristaltic flow acceleration. Electrode spacing is 1 cm, and the underside is a plane copper sheet electrode.

RF voltage of 4.5 kV rms. Titanium dioxide smoke generated from titanium tetrachloride was used to visualize the airflow above the panel. The velocity shear above the panel was high, with high velocities very near (1.0 mm) the surface, as will be seen in data presented below. At two cm above the panel, the velocity was reduced to a slow drift. As a definitive experiment, the electrode phasing was reversed, to reverse the direction of the traveling wave and the flow. This

flow reversal is documented in the video clip mentioned above. Two still images from that video clip are illustrated in Figure 4. In Figure 4a, the electrostatic wave propagates from left to right, taking the neutral gas flow with it. The phasing was reversed, and Figure 4b shows the resulting reversal in neutral gas flow velocity.

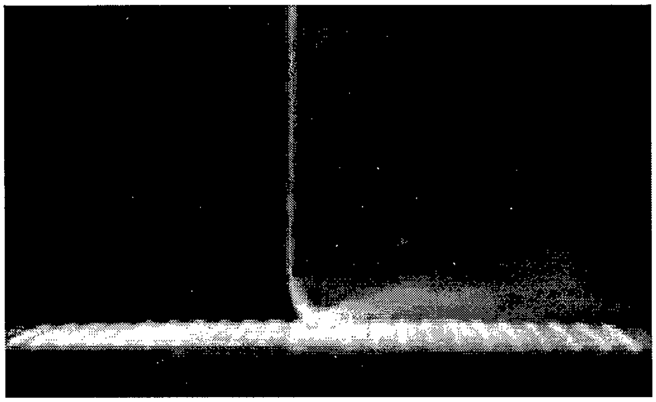


Figure 4a Traveling electrostatic wave to the right.

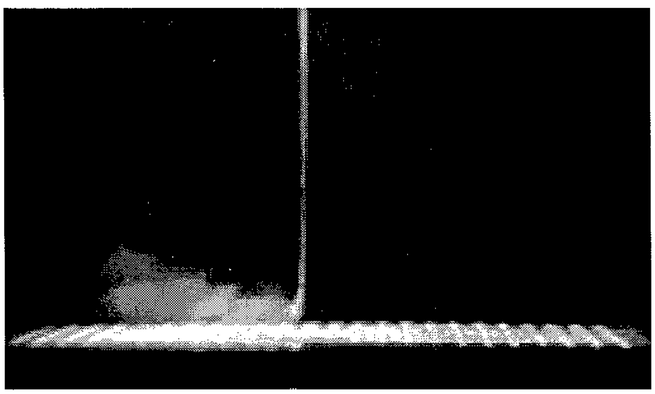


Figure 4b Traveling electrostatic wave to the left.

Figure 4. Single frames from a digital video showing the effect of the induced peristaltic velocity on titanium dioxide smoke emitted from a vertical tube 2.5 cm above the panel. a) Electrostatic wave propagating from. left to right b) Phase reversal, with electrostatic wave propagating from right to left.

3.) Development of Two Dimensional Electrohydrodynamic Plasma Actuators

A major goal of our current research program is to take flow field data that will help us improve key performance parameters of plasma actuators, such as the induced flow velocity and the efficiency of the flow acceleration process.

Paraelectric Plasma Actuators - We took wind tunnel measurements, with a Pitot probe, of the boundary layer flow field above and downstream of a ceramic paraelectric panel like that shown in Figure 5 below. The ceramic panels were made of 96% aluminum oxide (Al_2O_3). The active area covered by plasma actuators was 8.0 by 12 centimeters for all ceramic panels, and their outside dimensions were 10.2 by 14 centimeters. The ceramic panels fit flush into a recessed area machined into the base plate that formed the floor of the wind tunnel test section. Each

plasma actuator on the ceramic paraelectric panel of Figure 5 consists of two parallel electrode strips 0.06 mm thick on each side of the panel, displaced from each other with a gap of about 1mm. The plasma formed in the geometry shown in Figure 5 will accelerate the airflow to the left.

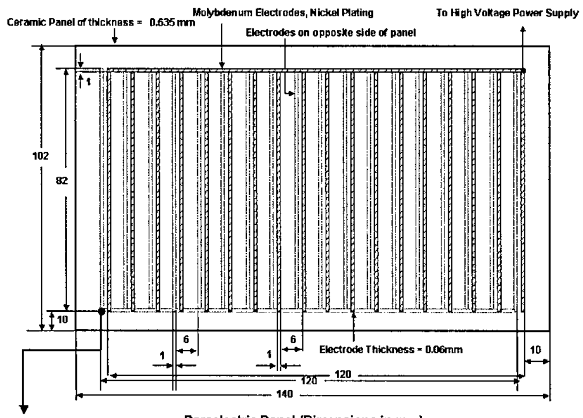


Figure 5 Paraelectric ceramic panel to accelerate boundary layer flows to the left.

Peristaltic Plasma Actuators - Shortly after initiation of the grant, we began quantitative measurements of peristaltic flow velocities initiated by circuit board panels such as that of Figure 3, and also of more robust aluminum oxide ceramic panels such as that shown in Figures 6 and 7 below. Our initial measurements were made in the 7 X 11 Low Speed Wind Tunnel at NASA LaRC by placing a 24-electrode circuit board panel in the test section, and placing one Pitot tube 1 cm from the final electrode on opposite sides of the panel, as shown in Figure 3. These Pitot tubes were 1.8 mm in inside diameter, and integrated the boundary layer velocity profile over this height. These tubes allowed us to measure the gross boundary layer velocity in both directions when the panel was energized.

Thus far we have observed, at an RF frequency of 6 kHz, velocities up to 10 meters per second; we have confirmed that the peristaltic velocity dominates the paraelectric flow velocity from the end electrodes; and we have seen a peristaltic velocity that is approximately linear with electric field, consistent with theory.

We also took similar flow field data from a ceramic "pure peristaltic" panel, the features and dimensions of which are documented in Figure 6, and a photograph of which is included as Figure 7. This panel has the same outside dimensions as the paraelectric panel of Figure 5, but in this case the lower electrode is a flat conducting sheet, as illustrated schematically in Figure 8. The peristaltic plasma actuators consist of twelve parallel electrode strips, each 0.06 mm thick and made of molybdenum plated with nickel. This thickness is less than the height of the maximum velocity of the induced wall jet of both paraelectrically and peristaltically induced flow, so the electrodes may be considered "flush", or embedded in the wall. These electrode strips are embossed on the top of the panel, displaced from each other by about one centimeter. The plasma is formed on both the upstream and downstream sides of the electrode as illustrated in Figure 8.

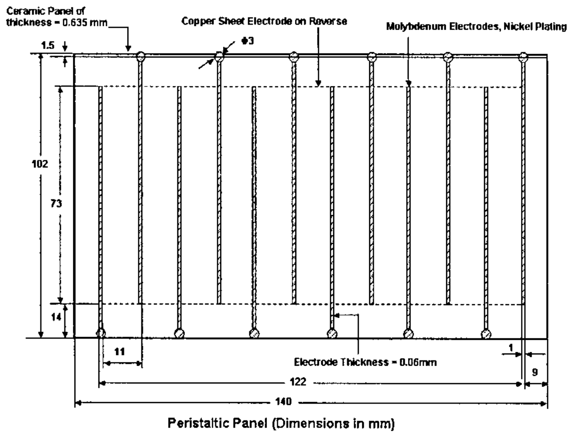


Figure 6 "pure peristaltic" ceramic panel with solid conducting sheet as bottom electrode.

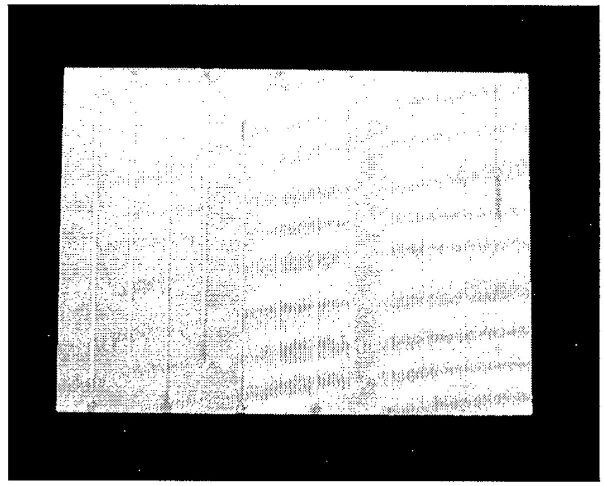


Figure 7 Digital image of an aluminum oxide "pure peristaltic" panel 0.635 mm thick with molybdenum electrodes coated with nickel 0.06mm thick on the upper surface, and a flat metal electrode on the lower surface (not visible).

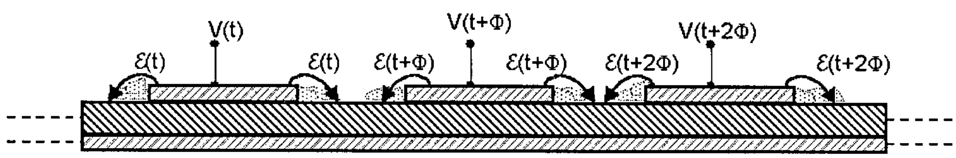


Figure 8 Pure peristaltic panel, with OAUGD plasma on both sides of plasma actuator electrode strip and a copper sheet as the bottom electrode.

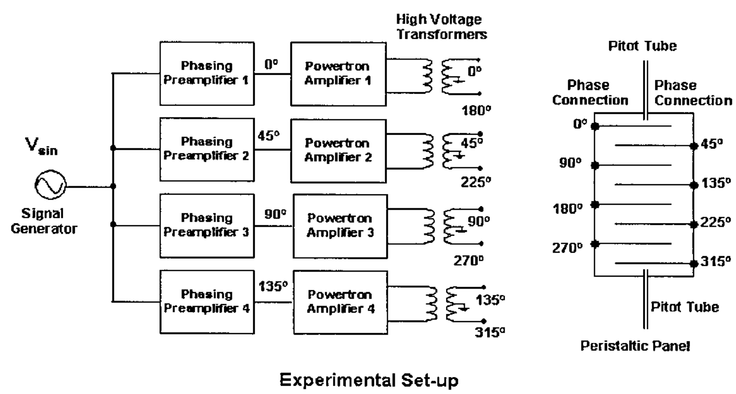
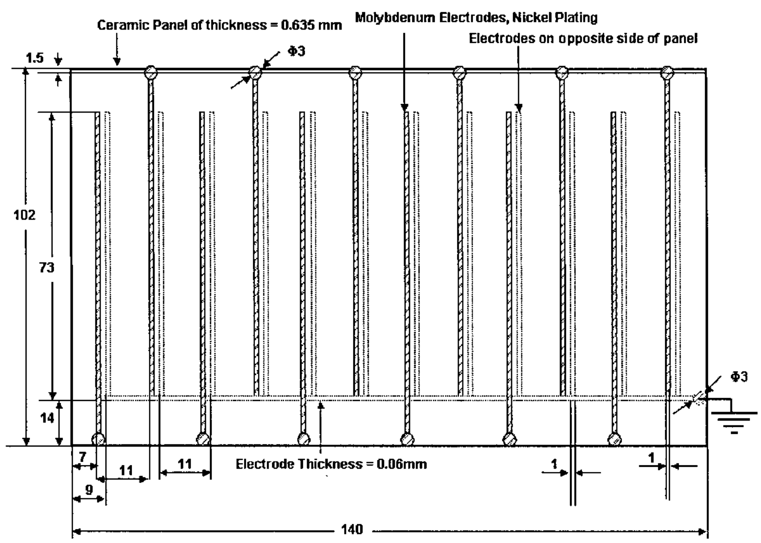


Figure 9 Polyphase power supply for peristaltic plasma acceleration.

For this panel, we have taken flow field measurements with the electrostatic traveling wave propagating toward and away from the Pitot tube, which is located 1.5 cm downstream from the last electrode on the right in Figure 3, as well as taking boundary layer profiles as a function of height above the panel. The individual actuators of the peristaltic and the combined

paraelectric and peristaltic panels were energized with the eight phase polyphase power supply illustrated in Figure 9.

Combined Peristaltic and Paraelectric Panel - Finally, we took a series of boundary layer profiles as vertical flow field traverses with a Pitot tube for the combined paraelectric and peristaltic panel documented in Figure 10. Each electrode of the panel is advanced at a phase angle of 45 degrees with respect to its preceding neighbor, thus providing peristaltic acceleration, but the lower electrode associated with each phase also forms a paraelectric flow accelerator that gives the flow an additional impetus in the direction of the traveling wave. This paraelectric assist improves the coupling of the traveling electrostatic wave to the plasma. Unlike the situation illustrated in Figure 8, the plasma is formed only on one (downstream) side of the actuator electrodes, so there is no counter-flowing vortex formation like that documented in our earlier work dating back to 1996. The ceramic panels are all of the same dimensions and made of the same materials, and constitute geometrically nearly identical two-dimensional flow acceleration devices. Only the electrode configurations and the electrical connections differ.



Combined Paraelectric and Peristaltic Panel (Dimensions in mm)

Figure 10 Combined paraelectric and peristaltic panel to accelerate flows to the right.

4.) Smoke Flow Studies of Paraelectric and Peristaltic Plasma Actuators

Experimental Apparatus - Smoke flow studies were made with apparatus available at the NASA Langley 7 x 11 Low Speed Wind Tunnel. The 25 micron diameter stainless steel smoke generating wire is mounted vertically 15 mm upstream from the first plasma actuator on the panel, at the panel midline. Before each run, the wire is wet with a special light mineral oil, the surface tension of which causes it to form approximately equally-spaced beads. With the plasma and wind tunnel flow conditions set at the desired levels, a current pulse is sent through the wire, which heats and causes the mineral oil to vaporize and produce approximately evenly spaced

smoke trails. These smoke trails, illustrated in Figure 11, are captured by a suitably synchronized camera and flash lamp.

Paraelectrically Enhanced Boundary Layer Flow - The paraelectric panel was placed in the wind tunnel with the free stream velocity set at 1.6 meters/sec. With the plasma off, the flow field above the panel was laminar, as shown in Figure 11, with a suggestion of boundary layer growth from some flow-tripping disturbance near the leading edge of the panel. When all of the paraelectric plasma actuators were energized to add momentum to the 1.6 meter/sec wind tunnel flow at the boundary, the flow lines became more laminar, as shown in Figure 12, and they

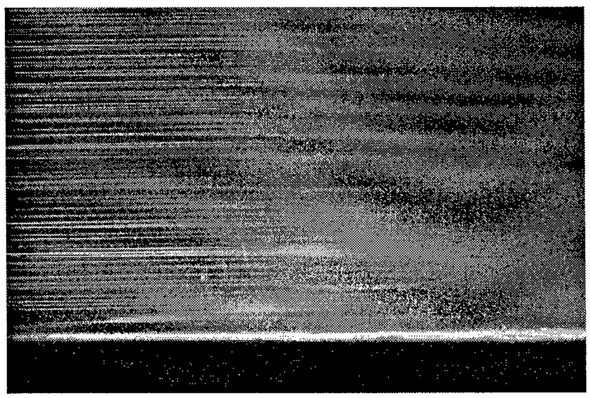


Figure 11 Smoke trails with wind tunnel velocity of 1.6 meters/sec and paraelectric plasma actuators off.

dipped down toward the panel. This descent of the flow lines is the result of the lower neutral gas pressure on the panel surface created by the presence of the plasma, and the pumping of the neutral gas to the right by Lorentzian momentum addition. In Figure 12, there is no evidence of counter-flowing boundary layer flow, turbulence generation, or a vertical component of the induced flow velocity that would produce an angled wall jet.

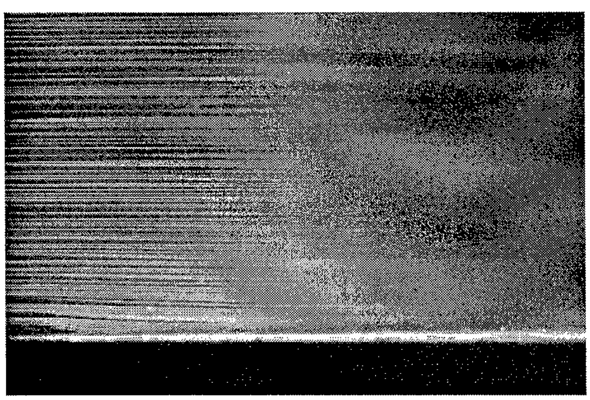


Figure 12 Smoke trails with wind tunnel velocity of 1.6 meters/sec and paraelectric plasma actuators energized.

Peristaltically Enhanced Boundary Layer Flow - As a paired comparison, a "pure peristaltic" panel like that documented in Figures 6 and 7 was installed in the wind tunnel. This panel generates a OAUGDP™ discharge on *both* sides of each actuator electrode, as illustrated in Figure 8. The airflow over the ceramic pure peristaltic panel of Figure 7, at a wind tunnel free stream velocity of 4.0 meters/second, and without the electrodes energized, is shown in Figure

13. When the electrodes were energized by the polyphase power supply of Figure 9 in such a way as to accelerate the gas flow to the right, the flow lines in the boundary layer assumed the turbulent character shown in Figure 14. The turbulence arises from the phenomenon illustrated in Figure 8 and documented in our previous studies of drag, whereby the plasma on both sides of the electrode creates a low pressure region there, and the descending flows of air are pumped by the plasma to the right and left. The flow to the right adds momentum to the boundary layer flow, but the flow to the left simply trips the flow into turbulence and results in the thickened boundary layer flow evident in Figure 14.

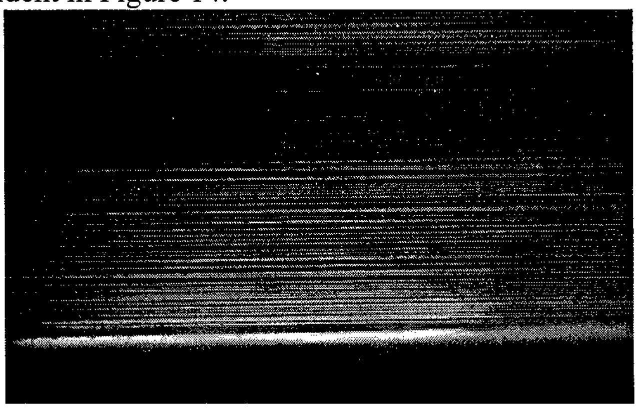


Figure 13 Boundary layer flow above a pure peristaltic panel with plasma actuators off and a wind tunnel velocity of 4.0 meters/sec.

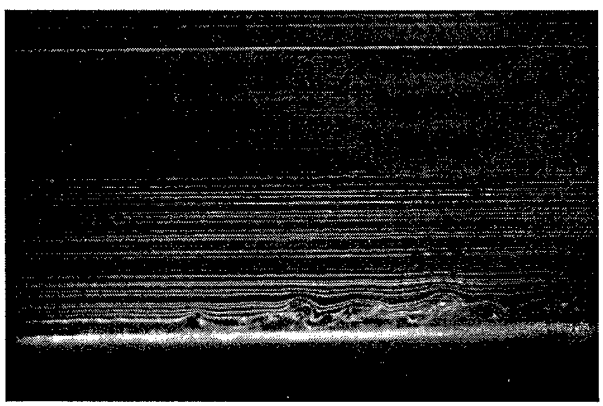


Figure 14 Wind tunnel flow of 4.0 meters/sec above a pure peristaltic ceramic panel with plasma actuators energized.

It is clear from Figure 14 that the "pure peristaltic" panel design of Figure 7, despite its simplicity, is an inferior plasma actuator because of the flow tripping and induction of turbulence associated with the paraelectric flows counter to the peristaltic wave and free stream velocity. Over the parameter envelope covered in these investigations, we did not see any cases in which the peristaltic effects so dominated the flow acceleration that the boundary layer of a pure peristaltic panel remained laminar, with parallel flow (or smoke) lines.

Combined Paraelectric and Peristaltic Boundary Layer Flow Enhancement - It is clearly desirable to add the paraelectrically induced flow from asymmetric plasma actuators to the

peristaltically induced flows from a phased array of electrodes. This can be done with the combined electrode geometry documented in Figure 10, which accelerates both flows in only one direction.

The panel documented in Figure 10 was mounted in the wind tunnel. The boundary layer and flow field, as revealed by smoke flow studies, was essentially identical to that of Figure 12 or 13 with the electrodes un-energized. When the panel was energized with 8 phase polyphase power so that the peristaltically and paraelectrically induced velocities add in the direction of the wind tunnel flow, the flow field becomes that shown in Figure 15. Here, the Lorentzian momentum is added to the flow in a laminar manner, and the resulting low pressure above the panel surface causes the flow lines to dip down toward the panel. This occurs in the absence of flow tripping or the generation of turbulence. It is clear that the electrode design of Figure 10 is to be preferred for peristaltic flow acceleration.

Another significant observation is that under no set of operating conditions, for any of the panel designs, did we observe flow lines that rose at an angle from the panel surface, as though vertically upward momentum had been added by the plasma actuator. The horizontal, laminar nature of the flow (except for the flow tripping of Figure 14) may be the result of keeping the upper electrodes of the plasma actuators on the panel surface much thinner than the height of the maximum of the wall jet velocity (0.06mm versus about 1mm, respectively).

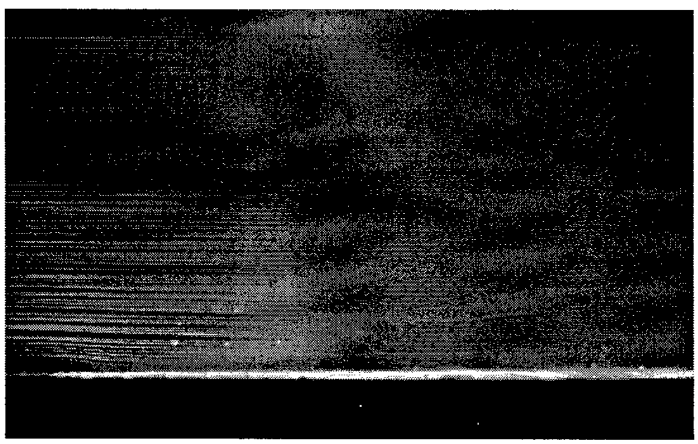


***Figure 15** Combined paraelectric and peristaltic plasma actuators energized to add momentum to the wind tunnel flow of 4.0 meters/sec.*

5.) Pitot Tube Measurement Of Boundary Layer Velocity Profiles

To better model the vertical velocity profile of the plasma actuators, we took Pitot tube measurements with the instrument shown in the photograph of Figure 16. The Pitot tube was mounted on the axis of the panel, with its opening 1.5 cm from the downstream edge of the last electrode on the upper surface of the panel. The vertical extent of the velocity profiles ranged from the surface up to 3 centimeters above the surface. In these measurements, no vertical sidewalls were erected at the edges of the panel to avoid out-flowing of the gas at the chord-wise panel edges.

Boundary Layer Profiles with Free Stream Flow - A set of characteristic boundary layer profiles from a combined paraelectric and peristaltic ceramic panel with a wind tunnel velocity of 1.6 m/sec is shown in Figure 17. The left-hand profile shows the classic boundary layer profile with the plasma actuators un-energized. The Pitot-system noise is evident below 0.5 m/sec. The right-hand profile shows the boundary layer profile with all 12 actuators on the panel energized in such a way as to add momentum to the boundary layer flow. This momentum

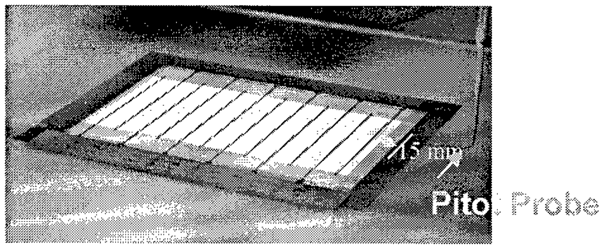


Figure 16 Combined peristaltic and paraelectric ceramic panel mounted in the wind tunnel. Arrows indicate the Pitot tube and position of Pitot tube opening 1.5 cm downstream of last actuator.

addition has been sufficiently effective in this case that the peak of the velocity profile is closer to the panel surface than the resolution of the Pitot tube positioning system, approximately 100 microns.

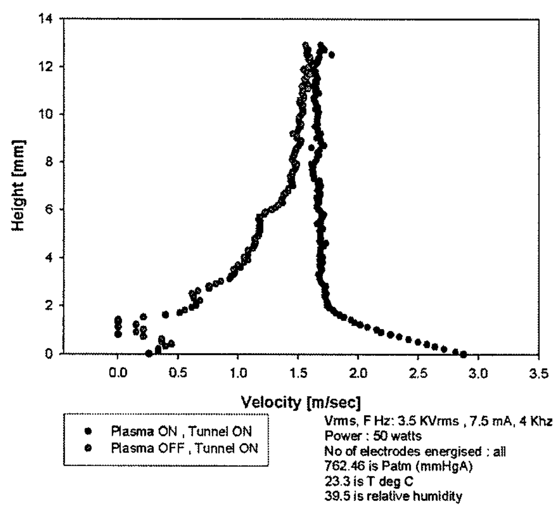


Figure 17 Pitot tube boundary layer velocity profiles taken with a wind tunnel velocity of 1.6 meters/sec, all 12 plasma actuators on panel energized at 3.5 KV rms, 4.0 kHz, and 50 watts total power.

Boundary Layer Flows in Static Air - An issue we wished to address during this research program was whether the addition of momentum to the boundary layer flow was linear with the number of plasma actuators in series, or whether a saturation occurred, due to flow sideways from the panel, boundary layer thickening, or other effects. To address this issue, we used the Pitot tube in the configuration of Figure 16 with the wind tunnel off, and energized successively the two actuators closest to the Pitot tube, then the four closest, and so forth until all 12 actuators were energized.

The results of these measurements are plotted in the three-dimensional graph of Figure 8 the axes of which are the flow velocity induced by the plasma actuators as measured by the Pitot tube, the number of electrodes energized, and the height above the panel surface. These data were taken at an RF voltage on the actuators of 3.5 kV and a RF frequency of 4.0 kHz. They show that the peak velocity is not linear with the number of actuators, but saturates after about 10 actuators are energized in series. The maximum of the velocity profile is at a height of about 1 mm at the Pitot tube position regardless of the number of electrodes energized.

Parametric Variations of Maximum Flow Velocity - Figure 18 indicates that the maximum induced flow velocity is initially linear, but becomes asymptotic as the number of plasma actuators is increased beyond 10. To assess the effect of the RF driving frequency of the plasma actuators on the induced flow velocity, the combined paraelectric and peristaltic panel of Figure 16 was operated in still air at an applied RF voltage of 4.5 kV with all 12 actuators energized.

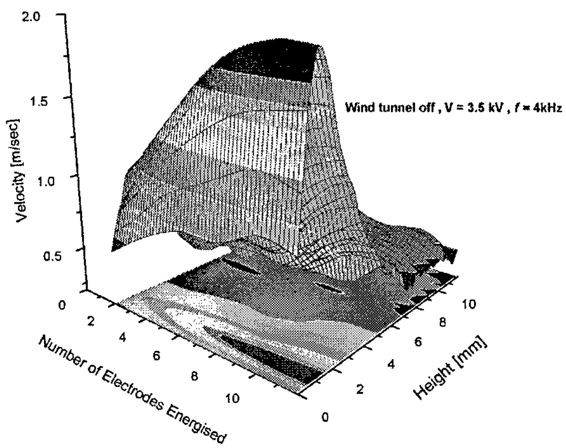


Figure 18 The induced wall-jet velocity 1.5 cm from the last plasma actuator as a function of the number of plasma actuators energized, and the height above the panel.

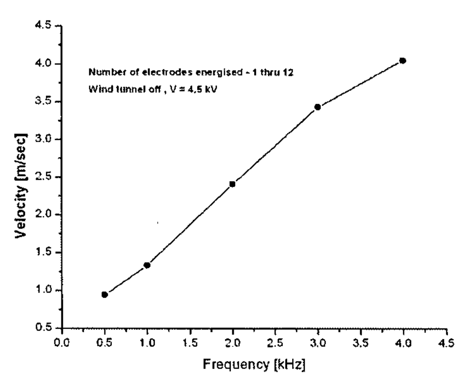


Figure 19 The maximum velocity of the wall jet as a function of RF frequency at a driving voltage of 4.5 KV, with all 12 actuators energized, and the wind tunnel off.

The results are plotted in Figure 19, which indicate that the maximum wall jet velocity increases linearly with RF frequency for the conditions of the test. These frequencies were all below the ion trapping frequency for the plasma actuators used, which is about 10 kHz.

The dependence of the maximum wall jet velocity on RF voltage for paraelectric and peristaltic excitation at an RF frequency of 6.0 KHz is shown in Figure 20 with all 12 electrodes energized. For these measurements, a combined paraelectric and peristaltic panel like that of Figure 16 was used. The paraelectric flow results were obtained by operating all 12 actuators in phase; and the combined paraelectric and peristaltic results were obtained with 8 phase polyphase excitation of the electrodes. These data indicate that the paraelectric mechanism was weaker than the peristaltic acceleration for these conditions. The velocity is a monotone increasing function of voltage in both cases, but the increase with voltage is much stronger for the peristaltic data.

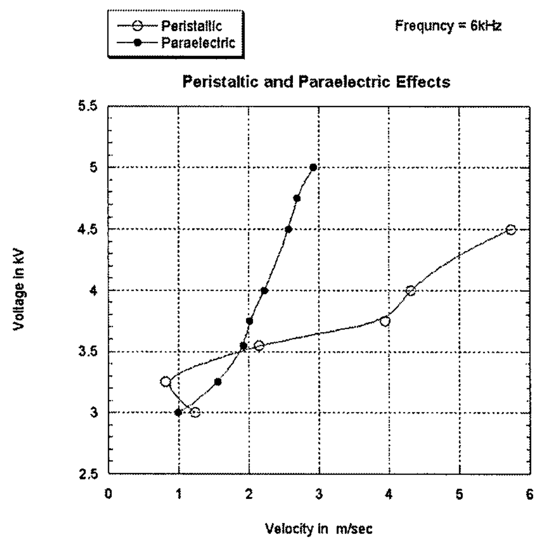


Figure 20 Peristaltically and paraelectrically induced velocities as functions of RF driving voltage on plasma actuators for a RF frequency of 6 kHz.

6.) Modeling the Plasma Actuator as a Glauert Wall Jet

It is useful to model the neutral gas wall jet produced by plasma actuators in terms already familiar to the aerodynamic community. The wall jet velocity profiles in still air illustrated in Figure 18 resemble that of the classical Glauert wall jet. While the Glauert wall jet is a laminar solution to the governing flow equations and is based on mass added to the flow at the wall, it is also a useful analytical tool for capturing the basic wall jet behavior as a point of reference for our current data.

Based on the intensity of light emitted from the discharge, the height of plasma above the panel is no more than about 0.5 mm in air at atmospheric pressure. When the accelerated laminar gas flow leaves the region of EHD interaction, the electrohydrodynamic body force becomes negligible, and the gas dynamic equations describing its motion have the same form as those of a laminar wall jet, analytically solved for the first time by M. B. Glauert in 1956. In this

model, the OAUGDP™ plasma actuator can be viewed as a narrow slit producing a Glauert wall jet.

The location of the Pitot tube during our velocity profile measurements (see Figure 16) was in the region of negligible EHD body force (15 mm from the last electrode), which enables us to fit our experimental data to Glauert's analytical formula, and find the value of F, the so-called *wall jet constant,* a measure of the wall jet "strength". Figure 21 shows some example results (provided by Dr. Jozef Rahel, NATO-NSF Postdoctoral Associate) of fitting our experimental boundary layer (laminar wall jet) velocity profiles for zero wind tunnel velocity to the Glauert wall jet theory. The sensitivity of the Pitot tube system and the zero-point accuracy were such that the minimum velocity that could be reliably measured with no background wind tunnel velocity was 0.5 meters/sec.

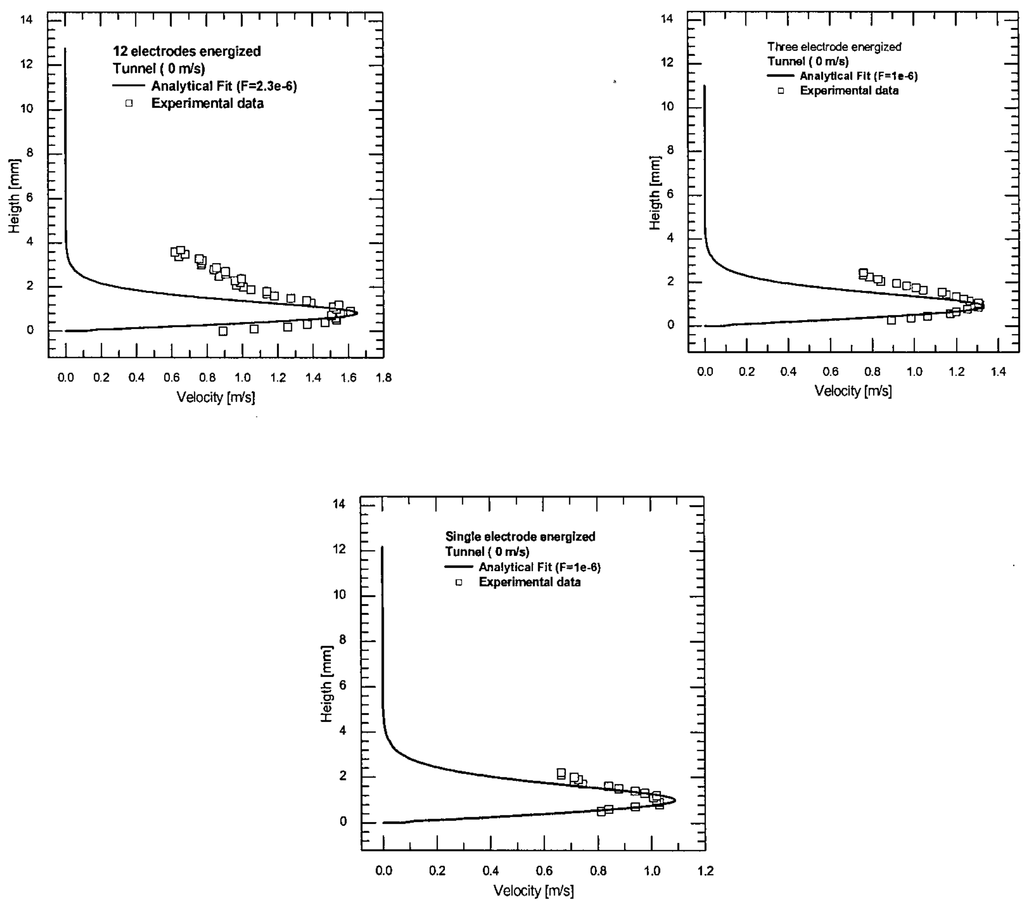


Figure 21: Laminar wall jet fit of experimentally obtained velocity profiles.

We can see excellent agreement when a single plasma actuator was energized. This agreement becomes slightly worse with an increase in the number of energized electrodes. A possible explanation is the effects of boundary layer growth as the flow passes over multiple electrodes. However, the qualitative agreement between our experimental data and the Glauert

wall jet fit is still good. The values of F obtained from these fits are within the range of (1-3) × 10^{-6} m^5s^{-3}.

7.) Three-Dimensional EHD Flow Acceleration Duct

This section contains a report of a proprietary EHD flow acceleration duct, an early version of which was developed under the auspices of Grant AF F49620-01-1-0425. A patent is is expected to be filed on this technology by the UT Research Foundation. Since this patent was developed under a DoD grant, US Government agencies will have the usual royalty-free license to use this technology. Here, we do not describe this technology in detail in this public document, but we do present some results of the operation of this device.

We developed an electrohydrodynamic (EHD) duct that can use paraelectric and peristaltic flow acceleration mechanisms either separately or in combination. The outlet of the duct can act like a Glauert wall jet to add momentum and gas flow to a boundary layer. Multiple versions of this EHD duct have been tested at this writing. Characteristic data from these tests is shown in Figure 22 below, in which pure paraelectric velocities greater than 9.0 meters/sec were observed. **The highest paraelectric velocity we have measured thus far is 9.5 meters/second,** and it appears that we can go beyond that by going to higher electric fields, higher frequencies, and additional serial electrodes in line. We have measured peristaltic velocities up to 7 meters/second, and we expect that with combined paraelectric and peristaltic effects, we will get at least the sum of these two velocities i.e. 16 meters/second.

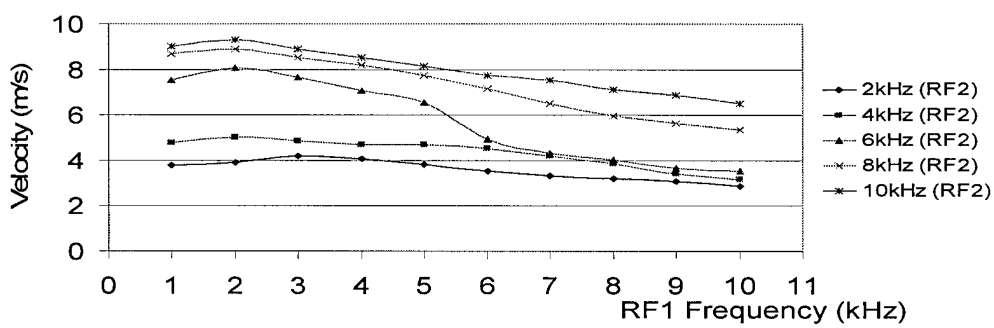


Figure 22 Paraelectric velocities from a 3-D EHD Glauert Duct

8.) Robustness of Plasma Actuators

A concern about plasma actuators is whether they are robust enough for flight applications, particularly the type of long-term, repeated use they might experience if mounted on the leading surfaces of aircraft wings for flow re-attachment or flow control. To this end, we put several panels containing plasma actuator strips through a series of tests to determine their performance under unfavorable conditions. These tests were documented by video images that are available at the "video" button of the Plasma Lab Web Site, http://plasma.ece.utk.edu.

Water Spray Test - The first test we conducted was to spray a heavy mist of water on an energized plasma actuator panel. The result of the water spray was to temporarily quench the plasma, but after the water spray ceased, the quenched area rapidly dried up as the plasma

advanced inwards from the periphery of the quenched area. This process took about 30 to 60 seconds to re-establish the plasma over the entire panel.

Maintenance and Wear - Another issue is whether the plasma actuators are robust enough to withstand normal wear, abrasion, and maintenance operations associated with flight aircraft. The question often asked of any drag reduction device mounted on the fuselage of an airplane is "Can you walk on it?" We tested this issue quite literally by energizing a 25 cm square plasma panel, and actually walking on the panel. Walking on an un-energized panel and then energizing it showed no visible effects such as might be expected from contamination and dirt. Actually walking on the energized panel quenched the plasma under the footprint of the Principal Investigator, but had no other apparent effect.

Electrical Safety - Finally, there is an understandable concern whether the energized panels can be made electrically safe so that anyone touching them will not be electrically shocked or otherwise harmed. We tested this by impedance matching the panel under test, and grounding the upper surface exposed to the atmosphere. Under these conditions, the plasma was generated in the normal manner, even with a grounding wand in contact with it, and direct contact with the Principal Investigator's hand gave no sensation of electrical shock or current flow.

9.) Development of Diagnostic Instrumentation for Atmospheric Glow Discharge Plasmas

An important part of our proposed research program is the development of plasma diagnostic instrumentation to measure the characteristics of the One Atmosphere Uniform Glow Discharge Plasma. Obtaining information about the electron number density, kinetic temperature, energy distribution functions, etc. is difficult because at one atmosphere, the electron collision frequency is higher than the frequency used in microwave interferometers, making their use problematical, and the electron mean free path is smaller than the Debye length, rendering Langmuir probe data very difficult to interpret. In addition to the lack of diagnostic methods in this regime, the surface plasma that produces the flow acceleration is only about 0.3 – 0.5 mm thick.

With the assistance of Co-PI Prof. Mostofa K. Howlader, we developed a new approach to diagnosing atmospheric glow discharge plasmas that has produced good results. This approach is based on using the propagation of cira 15 GHz microwave radiation through the plasma, and measuring its attenuation and slowing down (phase angle) with a microwave network analyzer. In spite of its extreme thinness, the surface plasma that produces paraelectric effects causes attenuation that is measurable with the network analyzer. We can relate the attenuation and phase angle to the electron number density and collision frequency through Appleton's equation. With these two quantities, one can obtain all the transport coefficients needed to model the plasma.

Results so far show time-averaged electron number densities between 10^{11} and 10^{12} /ccm. Results of measurements of the electron number density on a plasma surface layer have been reported in references 2 and 7, where this new diagnostic approach has attracted interest among the community investigating atmospheric plasmas. Our measurements so far have been time averaged, but Prof. Howlader has obtained, with about $20K of his new faculty member start-up

funds, the additional instrumentation needed to take time-resolved measurements of the electron number density and collision frequency. These time-resolved measurements will help understand the physics of these atmospheric glow discharge plasmas

As a recent demonstration of time-resolved plasma measurements with this technique, we measured the time-dependent electron number density and collision frequency during one period of the 60 Hertz excitation voltage of two fluorescent light tubes, one standard, and one of the new, "green" fluorescent light tubes containing less mercury. Our diagnostic method clearly showed the significant time-dependent differences between the two types of plasma. We have submitted further work on this diagnostic method as a proposal to Topic 22 of the DoD MURI program, where we hope to get funding to carry this diagnostic method forward, and to develop an instrument to apply it that costs a factor of ten less than our $310,000 network analyzer with its accessories.

10.) Advances in the Technology of Atmospheric Plasma Generation

EHD flow control offers many advantages over flaps and hydraulic-mechanical flight controls including instantaneous response to electrical actuating signals and no moving parts, but it also requires unfamiliar technologies such as high voltage, low frequency RF power supplies. For peristaltic plasma acceleration, polyphase power supplies are required in addition. Such power supplies are not generally available off the shelf because there has been no widespread commercial application to bring them on the market.

This situation has made it necessary for us to develop the specialized technology required of these power supplies. Mr. Zhiyu Chen, who has been supported by this grant, has been working on the problem of impedance matching the power supply to the plasma. Such matching reduces or eliminates the reflected power that otherwise would require an oversized power supply. His work under this grant has been accepted for publication [Refs. 5,6], and has appeared as papers at plasma meetings [Refs. 10, 16, and 19]. In addition to the issue of impedance matching, we developed a polyphase signal generator and power supply system [Refs. 1, 3] for peristaltic flow acceleration. In addition, we have done development work as necessary to avoid tracking and sparking of the high voltage RF needed to generate the OAUGDP™ plasma.

III OTHER ACTIVITIES SUPPORTED BY GRANT

1.) Collaborations

- Loaned power supply and advised Dr. Richard Rivir, AF Research Lab, WPAFB on OAUGDP technology.
- Gave seminar to Aero Department of the Air Force Academy on the OAUGDP and EHD flow control, November, 2001.
- Dr. Thomas McLaughlin of the Air Force Academy gave a seminar on AFA research in subsonic plasma aerodynamics at the UT Plasma Science Seminar, March 15, 2002.
- Invited seminar on subsonic plasma aerodynamics at the NASA LaRC in May, 2003.
- Four-week experimental campaign at the 7x11 Wind Tunnel at the NASA LaRC in May, 2003, two additional one week campaigns.

- Introduced Dr. Josef Rahel, a NSF-NATO Postdocoral Associate, to subsonic plasma aerodynamics. Dr. Rahel contributed to two conference papers, including one at the AIAA Reno meeting, and introduced the concept of modeling the plasma actuator as a Glauert wall jet.

2.) Innovations

- Successfully measured the electron number density of an atmospheric glow discharge only 0.3 mm thick.
- Developed an 8-phase polyphase RF power supply capable of operating from 0.5 to 10 kHz and up to 8 kV rms.
- Developed a microwave-plasma interaction diagnostic for atmospheric glow discharge plasmas to measure simultaneously the electron number density and the electron collision frequency. Submitted to 2004 MURI Topic 22 Program for further development.

3.) Technology Transitions

- Atmospheric Glow Technologies LLC, a spin-off company of the UT Plasma Sciences Laboratory, received a Phase I and Phase II SBIR award in the field of Plasma Aerodynamics from the Air Force. AGT has also received a Tibbetts Award from the Federal Government in Fall, 2001 for meritorious SBIR/STTR activities, and received an R&D 100 Award in 2002 for a product that had its origins in AFOSR – sponsored research.
- Two M. S. Theses, with two more to be completed in May, 2004
- Three archival journal articles, one in the Physics of Plasmas, two in the IEEE Transactions on Plasma Science
- In the period since initiation of this grant, the Principal Investigator has given 9 invited papers on the OAUGDP and subsonic plasma aerodynamic topics, one of them a plenary paper at an International IEEE meeting in Korea.
- Two AIAA Reno papers
- Twelve oral or poster presentations at IEEE or APS meetings.

IV PRESENTATIONS AND PUBLICATIONS SUPPORTED BY GRANT

During the period covered by this grant, it has not only supported the research program summarized above, but also the preparation of conference presentations, graduate training, and other related activities as follows:

1.) Two M. S. Theses, available on the Plasma Lab website, with two more to be completed in May, 2004, listed in Section A.
2.) Three archival journal articles, one in the *Physics of Plasmas*, two in the *IEEE Transactions on Plasma Science*, listed in Section B.
3.) Two AIAA Reno papers, listed in Section C.
4.) Two invited papers on subsonic plasma aerodynamics, one of them a plenary paper at an International IEEE meeting in Korea, listed in Section D.

5.) Twelve oral or poster presentations at IEEE or APS meetings, listed below in Section D.
6.) Presented an invited seminar on subsonic plasma aerodynamics at the NASA Langley Research Center in May, 2003.
7.) Four-week experimental campaign at the 7x11 Low Speed Wind Tunnel at NASA Langley Research Center in May, 2003, two other campaigns of one week each.

A) M. S. Theses at the University of Tennessee

1.) Sin, H. *"A Polyphase Power Supply and Peristaltic Flow Accelerator Using a One Atmospheric Uniform Glow Discharge Plasma".* (6Mb). M.S. in Electrical Engineering Thesis, Department of Electrical and Computer Engineering, University of Tennessee, Knoxville, December, 2002.

2.) Yang, Y. *"Time Resolved Measurements of Plasma Electron Number Density and Electron-Neutral Collision Frequency Using a Microwave Diagnostic Method".* (884Kb). M.S. in Electrical Engineering Thesis, Department of Electrical and Computer Engineering, University of Tennessee, Knoxville, December, 2003

3.) Madhan, R. C. M.: "Boundary Layer Flow Acceleration by Paraelectric and Peristaltic EHD Effects of Aerodynamic Plasma Actuators" (provisional title). M.S. in Electrical Engineering Thesis, Department of Electrical and Computer Engineering, University of Tennessee, Knoxville, May, 2004.

4.) Yadav, M.: GRA, "Experimental Pitot Tube Studies of the Flow Induced by OAUGDP Plasma Actuators" (provisional title). M.S. in Electrical Engineering, Department of Electrical and Computer Engineering, University of Tennessee, Knoxville, May, 2004

B) Archival Journal Articles

5.) Chen, Z.: "Impedance Matching for One Atmosphere Uniform Glow Discharge Plasma (OAUGDP™) Reactors". *IEEE Trans. On Plasma Sci.,* Vol. 30 No. 5, October 2002 pp 1922-1930.

6.) Chen, Z.: *"PSPICE Simulation of One Atmospheric Uniform Glow Discharge Plasma (OAUGDP) Reactor Systems", IEEE Trans. On Plasma Sci.,* Vol. 31 No. 4, August 2003 pp 511-520.

7.) Roth, J.R.: "Aerodynamic Flow Acceleration using Paraelectric and Peristaltic Electrohydrodynamic (EHD) Effects of a One Atmosphere Uniform Glow Discharge Plasma", *Physics of Plasmas*, Vol. 10, No. 5 (2003).

C) Archival Conference Papers

8.) Roth, J. R., Sin H., Mohan R.C.M. and Wilkinson S. P.: *"Flow Re-attachment and Acceleration by Paraelectric and Peristaltic Electrohydrodynamic Effects",* Paper AIAA 2003 - 531, Proc. 41st Aerospace Sciences Meeting and Exhibit, 6-9 January, 2003, Reno, NV.

9.) Roth, J. R.; Madhan, R. C. M.; Yadav, M.; Rahel, J.; and Wilkinson, S. P.: *"Flow Field Measurements of Paraelectric, Peristaltic, and Combined Plasma Actuators Based on the One Atmosphere Uniform Glow Discharge Plasma (OAUGDP™)"* Paper AIAA 2003 - 845, Proc. 42nd Aerospace Sciences Meeting and Exhibit, 5-8 January, 2004, Reno, NV.

D) Invited Papers, Poster Papers, and Progress Reports at Meetings

10.) Chen Z. and Roth J. R. (2001): "Impedance Matching for One Atmosphere Uniform Glow Discharge Plasma (OAUGDP) Reactors", Paper P2H-15, *Proceedings of the 28th IEEE International Conference on Plasma Science*, Las Vegas, NV, June 17-22, 2001, ISBN 0-7803-7141-0, p 313.

11.) Roth J. R. (2001): "Subsonic Plasma Aerodynamics using Paraelectric and Peristaltic Electrohydrodynamic (EHD) Effects". *Proceedings of the 29th IEEE International Conference on Plasma Science*, Banff, Alberta, Canada, May 26-30, 2002, p 95, ISBN 0-7803-7407-X.

12.) Howlader M., Yang Y., and Roth J. R. *"Time Averaged Electron Number Density Measurement of a One Atmosphere Uniform Glow Discharge Plasma (OAUGDP) by Absorption of Microwave Radiation",* Paper 5P-29, Proceedings of the 29th IEEE International Conference on Plasma Science, Banff, Alberta, Canada, May 26-30, 2002, p 271, ISBN 0-7803-7407-X.

13.) Sin H., Madhan R., and Roth J. R. "A Polyphase Power Supply and Peristaltic Flow Acceleration System Using a One Atmosphere Uniform Glow Discharge Plasma (OAUGDP)", Paper2P-09, *Proceedings of the 29th IEEE International Conference on Plasma Science*, Banff, Alberta, Canada, May 26-30, 2002, p 146, ISBN 0-7803-7407-X.

14.) Howlader M., Yang Y. and Roth J. R. *"Measurement of Electron Number Density and Collision Frequency in a One Atmosphere Uniform Glow Discharge Plasma using a Microwave Network Analyzer",* Paper GTP-055, Presented at the 55th APS Gaseous Electronic Conference, Minneapolis, Minnesota, October 15-18, 2002, APS Bulletin, Volume 47, No.- 07 (2002), Page - 24.

15.) Sin H., Madhan R., Roth J. R. *"Subsonic Plasma Aerodynamics using Lorentzian Momentum Transfer in Atmospheric Normal Glow DischargePlasmas",* Paper YF2-004, Presented at the 55th APS Gaseous Electronics Conference, Minneapolis, Minnesota, October 1.)5-18, 2002, APS Bulletin, Volume 47, No.- 07 (2002), Page -78.

16.) Chen Z and Roth J. R. *"PSPICE Simulation of One Atmospheric Uniform Glow Discharge Plasma (OAUGDP) Reactor System",* Paper QWP-084, Presented at the 55th APS

Gaseous Electronic Conference, Minneapolis, Minnesota, October 15-18, 2002, APS Bulletin, Volume 47, No.- 07, (2002), Page - 53-54.

17.) Roth J. R. **(Invited).** *"Aerodynamic Flow Acceleration using Paraelectric and Peristaltic Electrohydrodynamic (EHD) effects of a One Atmosphere Uniform Glow Discharge Plasma (OAUGDP)",* Paper C12-006, Presented at the Annual Meeting of the APS Plasma Physics Division, Orlando, FL, November 11-15, 2002, APS Bulletin, Volume 47, No. 09 (2002), Page - 58.

18.) Roth J. R. **(Invited Plenary Paper):** *"Subsonic Plasma Aerodynamics using a One Atmosphere Uniform Glow Discharge Plasma (OAUGDP)",* Proceedings of the 30th IEEE International Conference on Plasma Sciences, Jeju, Korea, June 2-5, 2003, Page 181, IEEE Catalog No. 03CH37470, ISBN 0-7803-7911-X.

19.) Chen Z. and Roth J. R *"PSPICE Simulation of One Atmospheric Uniform Glow Discharge Plasma (OAUGDP) Reactor Systems",* Paper 3PA-54, Proceedings of the 30th IEEE International Conference on Plasma Science, Jeju, Korea, June 2-5, 2003, Page 299, IEEE Catalog Number 03CH37470, ISBN 0-7803-7011-X.

20.) Yang Y., Howlader M. and Roth J. R. *"Measurement of the Electron Density and Collision Frequency of a Fluorescent Light Tube Plasma using a Novel Microwave-Based Diagnostic Technique",* Paper 1PA11, Proceedings of the 30th IEEE International Conference on Plasma Science, Jeju, Korea, June 2-5, 2003, Page 147, IEEE Catalog Number 03CH37470, ISBN 0-7803-7011-X.

21.) Madhan R., Yadav M., Roth J.R. and Wilkinson S. *"Aerodynamic Flow Control by Peristaltic Acceleration of a One Atmospheric Uniform Glow Discharge Plasma",* Paper 5A07, Proceedings of the 30th IEEE International Conference on Plasma Science, Jeju, Korea, June 2-5, 2003, Page 320, IEEE Catalog Number 03CH37470, ISBN 0-7803-7911-X.

22.) Roth J. R., Madhan R., Rahel J. and Yadav M. *"Aerodynamic Boundary Layer Control Using EHD Effects of a One Atmosphere Uniform Glow Discharge Plasma (OAUGDP)",* Paper GTP 024, Proceedings of the 2003 APS Gaseous Electronics Conference, October 21-24, 2003, San Francisco, California.

23.) Roth J. R., Rahel J. and Dai X. *"Three Dimensional Flow Acceleration Using Plasma Aerodynamics Actuators",* Proceedings of the 2003 APS Gaseous Electronics Conference, October 21-24, 2003, San Francisco, California.